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Research article

Mitigating moisture stress in *Brassica juncea* through deficit irrigation scheduling and hydrogel in ustocherpts soils of semi-arid India

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ABSTRACT

A field experiment was conducted to study the effect of irrigation scheduling and use of superabsorbent polymers on growth, seed and water productivity, soil moisture dynamics in Indian mustard under semi-arid conditions. During the first year of the study, the increase in the mustard seed yield with irrigations applied at IW/CPE (Irrigation water, mm/Cumulative Pan Evaporation, mm (CPU) ratios 0.8, 0.6, 0.4 and no-irrigation (rainfed) with hydrogel application (+HG) was 18.6, 17.9, 14.4 and 28.3%, respectively, over no hydrogel (-HG). The seed yield enhancement by hydrogel application during the second year varied from 3% under sufficient irrigation to 24.9% under rainfed conditions. The pooled data indicated that the production indices and economics with hydrogel use improved significantly ($P \leq 0.05$) under limited irrigation or rainfed condition. A net increase of 38, 27.7, and 10.7%, in production efficiency (PE), the net return, and profitability of mustard respectively was observed due to the use of hydrogel improved under the rainfed condition. Under limited irrigation (single irrigation at IW/CPE 0.4), a net increase of 24.2 and 31.8%, in the marginal and gross water productivity of mustard respectively, was recorded with hydrogel use. Similarly, in rainfed conditions, hydrogel increased gross water productivity by 22.6%. The energy intensity under irrigations scheduled at IW/CPE 0.8, 0.6, 0.4, and rainfed condition, was enhanced by 4.9, 5.9, 6.7, and 10.5%, respectively, due to hydrogel application. Thus, the use of hydrogel both under the rainfed condition and deficit irrigation has the potential to enhance productivity, profitability, and bio-energy output of Indian mustard in semi-arid agro-ecologies.

1. Introduction

Vegetable oil has one of the highest shares (40%) of the production of all agricultural commodities globally. India is the largest importer of edible oils ($10.5 billion) in the world followed by China & the USA. India's share of world edible vegetable oil imports is about 15% (FAO 2019). Indian vegetable oil economy is the world's fourth-largest after the USA, China, and Brazil with total oilseed production of 34.2 million tonnes (Mt) during 2019–20. Oilseed cultivation is undertaken across India in an area of 26.0 Million hectares (Mha), mainly on marginal lands, dependent on monsoon rains (un-irrigated), and with low levels of input usage. Among oilseed crops, rapeseed-mustard is important crop, cultivated in approximately 6.0 Mha area with 9.1 Mt production and 1397 kg/ha productivity. India holds the third position in the world in rapeseed-mustard oil production after China and Canada during 2018–19 (Anonymous 2019). Rapeseed-mustard is the largest contributor to the total domestic edible oilseed production (31.3%), followed by soybean (*Glycine max* (L.) Merr.) and groundnut (*Arachis hypogaea* L.) with a contribution of 26.1%with 24.8%, respectively. Its acreage (24.2%) however remains second to soybean (46.0%) among all oilseed crops (Anonymous 2018) in India. Indian mustard (*Brassica juncea* Cosson and Czern L.) shares the major area occupied by this group and anchoring the livelihood of the majority of the farmers in the semi-arid regions of India. It is mostly grown in rainfed ecologies using conserved monsoonal rainwater supported by a few wintry showers. Its cultivation, thus, has confined 50% of its total area in one state of the country (Rajasthan). This area-wise largest state is located in the north-western end of the country and characterized by light-textured soils with low water holding capacity and poor soil fertility (Based on available N (120–180 kg ha^{-1}), P_2O_5(10–18 kg ha^{-1}, K_2O (200–250 kg ha^{-1}) and low soil organic carbon (<0.25%). Similarly, challenged ecologies in the other parts of the globe (Africa, Asia, South America, even North America) are suited for the cultivation of Indian mustard. With efficient crop management in these areas, rapeseed-mustard can sustain the livelihood of a large number of

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farmers. The sound management practices for rapeseed-mustard are needed for efficient use of limited moisture, available during the crop season especially at critical stages of crop growth, high evaporative demand (2–6 mm day^{-1}), low (<0.25%) soil organic carbon, and poor crop management, which are restricting the national average productivity of oilseed Brassicas to 1.09 t ha^{-1}, as compared to the world's average of 1.83 t ha^{-1} (DRMR, 2013, Rathore et al., 2019; Mandal et al., 2011) in India. Efficient irrigation water management in rapeseed-mustard has an enormous impact on seed and oil products and also on response to other applied inputs (Rathore et al., 2019). Besides efficient irrigation water management, improved rainwater and soil moisture conservation help in enhancing crop growth and yield as well. The successful cultivation of the crops in semi-arid areas during *rabi* (winter season) is mainly dependent upon the conserved soil moisture of previous *Kharif* (rainy season). In this scenario, superabsorbent polymers (hydrogels) may be of high significance. In mustard-growing areas, generally, one- irrigation during the crop period is being practiced. However, mustard crop cultivation with only one-irrigation, to be worst management through the check basin method, is responsible for lower water-use efficiency (WUE) of 35–40% (Rathore et al., 2014b). Irrigation through check basin often results in the excess water supply at one stage and moisture deficit at the other growth and phenological stages, eventually consequence in poor growth and photosynthetic rate, less branching, and finally lower seed yield (Singh et al., 1991; Rathore et al., 2014a). Therefore, limited water needs to be precisely scheduled through micro-irrigation for higher WUE and crop productivity (Rathore et al., 2014a,b).

Under deficit water availability, recent water management techniques, *viz.* precise irrigation scheduling, fertigation, and use of superabsorbent polymers with high water holding capacity, bio-compatibility, and synthetic flexibility raise new hopes to enhance crop productivity and WUE under declining water resources by improving water relations in sandy soils (Seliktar, 2012; Dai et al., 2017; Yangyuoru et al., 2006). Under limited irrigation water availability, the use of synthetic polymers improves water availability to plants by restricting the drainage of water beyond the root zones (Narjary et al., 2012). These polymers absorb the conserved rain and other moisture, release it gradually at later stages to meet the water requirement of the crop, and also prolong the irrigation interval (El-Hady and Camilia, 2006; Allahdadi et al., 2005). The hydrogels reduce nutrient losses by preventing leaching, especially nitrogen and potassium. It, thus, promotes synchrony in nutrient release and uptake of nutrients as needed by crop plants (Pirmoradian et al., 2004). The improvement in seed germination and seedling survival (Johnson and Leah, 1990; Ahmad and Verplancke, 1994), and higher biomass production (Dass et al., 2013; Yezdani et al., 2007) with the use of polymers enhance yield (Rehman et al., 2011). Hydrogel remains safe and non-toxic and eventually decomposes to carbon dioxide, water, and ammonium and potassium ions, without any residue (Mikkelsen 1994; Trenkel 1997). However, there are contrasting reports also which have shown little to no response of hydrogels (Ingram and Yeager, 1987; Wang 1989; Leciejewski 2009; Paluszek and Zembrowski, 2008), thus, its agronomic evaluation on drought mitigation and impact on yield, keeping the crop, soil texture, and type, and weather in consideration, is urgently needed to develop efficient irrigation scheduling under limited water resources. The present work thus aims to determine the effect of hydrogel under micro-irrigation on growth, productivity, soil moisture release pattern, irrigation WUE and sustainability of Indian mustard under semi-arid conditions.

2. Materials and methods

2.1. Prevailing weather and site description

The weather conditions during the growing season of the crop have been described in Table 1. The maximum temperature ranged between 19.1–33.8 °C and 17.0–32.1 °C during 2013–14 and 2014–15, respectively. Rainfall data were recorded using a rain gauge installed at the experimental site (monthly rainfall data has been provided in Table 1). During 2013–14, a 29.7 mm rainfall was received in a single day during crop season, that too in February coinciding with the terminal stage of the crop. During 2014–15, a comparatively higher ambient temperature at crop establishment period led to higher moisture stress consequent to evaporative losses during 2013–14, but an evenly distributed higher rainfall of 130 mm (~4.4-fold higher over 2012–13) maintained a favorable soil moisture regime during the important phenological crop growth phases (Table 1).

The experiment was conducted at the Directorate of Rapeseed-Mustard Research, Bharatpur, India ($27^{0}15'$ N latitude and $77^{0}30'$ E longitude, 178.37 m above mean sea level) during the winter seasons of 2013–14 and 2014–15. The soil of the experiment site was clay loam in texture (32% sand, 38 % silt, and 30 % clay) and sodic (pH EC and ESP varied from 8.5–9.5, 0.8–0.9 dS m^{-1} and 15.8, respectively) in nature. The soil samples were drawn from a depth of 0–15 cm using an auger with a 5 cm internal diameter. Soils were low in organic carbon (2.1 g kg^{-1}); $KMnO_4$ oxidizable N (130 kg ha^{-1}); medium in 0.5 N $NaHCO_3$extractable P_2O_5 (21.5 kg ha^{-1}) and 1.0 N NH_4OAc exchangeable K_2O (260 kg ha^{-1}). The bulk density of the soil was 1.50 Mg m^{-3} and the infiltration rate 4.5 mm h^{-1}. Soil moisture at field capacity wilting point was 27–28%, 6.4–7.5%, whereas, hydraulic conductivity was 6.4–7.5 cm/s.

2.2. Treatment description, the record of observations, and crop management

The experiments were conducted in strip plot design with four irrigation management comprising, Unirrigated (rainfed), irrigation scheduling at IW/CPE ratio 0.4, 0.6, and 0.8, with and without hydrogel (+HG and -HG) application replicated thrice. For a specific IW/CPE ratio, the irrigation water of 20 mm was applied on reaching a specified value of CPE (mm). The CPE values were taken from an open pan evaporimeter from the weather observatory. Rainfed were maintained with and without hydrogel use. The hydrogel is a biopolymer-based super-absorbent hydrogel of a polyacrylate family. The gel is obtained through free radical solution polymerization, grafting, and cross-linking of acrylamide onto a derivative of cellulose with approximately 50% add-on. It absorbs

Table 1. Weather conditions during crop period in 2013–14 and 2014–15.

Month	Temp (°C)				Mean RH (%)				Rainfall (mm)		Pan (mm/day)	evaporation
	Max.		Min		0720 h		1420 h					
	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15
October	32.1	34.6	20.1	18.9	87.0	79.9	51.3	36.1	30.8	2.4	3.2	3.6
November	27.9	30.2	11.1	12.0	86.4	80.8	49.4	28.4	6.0	0.0	2.4	2.0
December	22.4	20.6	7.7	6.2	93.5	92.3	58.1	52.8	13.3	0.0	1.4	1.2
January	17.0	16.9	7.4	7.4	98.0	98.3	77.2	74.1	55.7	39.3	0.6	0.4
February	21.6	25.9	8.5	10.5	95.1	94.2	62.9	52.3	10.4	0.0	1.5	2.1
March	29.4	28.7	13.2	14.9	88.4	90.9	42.9	61.8	13.8	57.0	3.2	2.3

more than 350–500 g of water/gram of the xerogel (dry polymer), and therefore, is termed as superabsorbent hydrogels (IARI 2012). The complete mixing of the hydrogel in the top 8–10 cm of the soil before sowing at the time of the last plowing was done. The other important characteristics of the hydrogel are given in Table 2. The SAP-hydrogel was applied in powdered form at the rate of 5.0 kg/ha and mixed with the dry seed. The hydrogel was applied along with the seed through a mustard seed drill in the field.

The mustard crop cv. NRCDR 02 was sown in the winter season (the first fortnight of October) during both study years. The seeds were sown at the rate of 5 kg ha^{-1} at 30 × 10 cm spacing at a depth of 3–4 cm with a seed drill. The seeds were treated with carbendazim 2.0 g kg^{-1} seed and metalaxyl (Apron 35 SD) 6.0 g kg^{-1} seed for protection against stem rot and white rust diseases, respectively, before sowing. The plant-to-plant distance was maintained at 10–15 cm by thinning 15–20 DAS (days after sowing). The nitrogen dose was 80 $kgha^{-1}$, variable doses of nitrogen (N) were given according to the sub-plot treatments. Phosphorus (P_2O_5, 40 kg ha^{-1}) as di-ammonium phosphate and potassium (K_2O, 40 kg ha^{-1}) as muriate of potash were applied as basal at the time of land preparation. Half a dose of N and a full dose of P and K were applied as basal, whereas the remaining N in the form of urea was applied through fertigation through the micro-irrigation system. Fertigation of N through urea was done along with the micro irrigation system with the help of eventually working at the pressure of 1.5 kg cm^{-2}. The crop was harvested through a combine and the seed and biomass yields were recorded plot-wise.

The irrigation scheduling in mustard was done through a micro-sprinkler system based on soil matric potential and IW/CPE value. The volume of water applied under various IW/CPE ratios was calculated as per the procedure described by Brouwer and Heibloem (1986) in irrigation water management training manual No. 3. The total amount of water applied (input water) was computed by summing up irrigation water and rainfall. The total water balance was computed considering the irrigation water applied contribution from rainfall and water productivity. The tensiometers (16) were installed at a depth of 0–30 cm, as >70% water is being absorbed by the plant from this depth. The soil moisture tension was recorded at regular intervals with the help of tensiometers, which were having a range of matric potential from 0-100 cb (centibar). The relative water content (RWC) in mustard leaf was measured at pre-flowering and pod-filling stages and it is being estimated in % from fresh, dry, and turgid weight of the leaf. Various growth, water productivity, and energy parameters were computed using the equations, as shown in Table 3:

Table 2. Important characteristics of Pusa-hydrogel.

Parameters	Characteristics
Chemical constitution	Cellulose based grafted and cross-linked anionic polyacrylate
Appearance	Amorphous, granulous
Particle size	20–100 mesh (micro-granules)
pH	7–7.5
Stability at 50 °C	Stable
Minimum absorption in deionized water	350 g g^{-1}
Sensitivity to UV light	None
Temperature of maximum absorption	50° C
Time taken for 60% swelling	2 h. (Approx.)
Stability in soil	<2 years
Toxicity in soil	None

Table 3. Expressions for computation of various growth, water productivity and energy parameters in Indian mustard.

Parameter	Unit	Expression
Water productivity (WP)	kg ha-mm^{-1}	$WP = \frac{Y}{CU}$
Marginal water productivity (WP_m)	kg ha-mm^{-1}	$WPm = \frac{Y}{We}$
Gross water productivity (WP_t)	kg ha-mm^{-1}	$WPt = \frac{Y}{Wi + Wr}$
Production efficiency (PE)	kg ha^{-1} day^{-1}	$PE = \frac{Y}{n}$
Net energy (E_n)	MJ ha^{-1}	$En = Eo - Ei$
Energy efficiency (E_e)	MJ ha^{-1}	$Ee = Eo/Ei$
Energy productivity (E_p)	MJ ha^{-1}	$Ep = BY/Ei$
Energy intensity (E_{in})	MJ Re^{-1}	$Ein = Eo/COC$
RWC	%	FLW-DLW/TLW-DLW

where; Y is mustard yield (kg ha^{-1}), CU is the consumptive use of water (mm), W_e is the irrigation water applied, W_{i+r} is the total water available through irrigation and rainfall (mm), n is the duration of the crop (days), E_o is the energy output (MJ ha^{-1}) and E_i is the energy input(MJ ha^{-1}), BY is the biomass yield (kg ha^{-1}) and COC is the cost of cultivation (Rs ha^{-1}).FLW is fresh leaf weight, DLW dry leaf weight, TLW is the turgid leaf weight.

2.3. *Data collection and statistical analysis*

The soil samples from each plot (total 24) were taken at 0–15 cm soil depth for analysis of available N, P, and K. The irrigation water was also analyzed for the salt load (TDS), pH, EC. The quantification of irrigation water was done with the help of a water meter, fitted in the mainline. Observations on plant growth, phenology, and yield attributes were recorded (Main shoot length (M S), Branches/plant, total siliquae/plant, 1000 seed weight, gm, Seed yield (kg ha-1), Biological yield (kg ha-1) and Oil yield (kg ha^{-1}). The cost of cultivation was computed following the guidelines of the Commission of Cost and Prices, Govt. of India, and the B: C ratio was estimated by dividing the net returns from the cost of cultivation (minimum support price of mustard). The government is promoting irrigation through micro-irrigation systems and hence provides a subsidy for the benefit of stakeholders. The economics of micro-irrigation systems has been assessed based on a 100% subsidy. Depth-wise monitoring of soil moisture content on a weight basis through the gravimetric method, as well as soil moisture tension through tensiometers, was done. The volumetric soil moisture estimation was done from 48 samples at the pre-flowering and pod development stages. The experiment was laid down in two factorial randomized block design with three replications. Data on yield attributes, production efficiency, and economics were pooled and analyzed while remaining data were analyzed on yearly basis. The mean data were statistically analyzed using Fisher's analysis of variance technique and the treatment means were compared by the DMR test at the level of 0.05 probabilities. The statistical analysis was done for two factors use of hydrogel and irrigation scheduling. It is more useful than the LSD when larger pairs of means are being compared, especially when those values are in a table. DMRT tends to require larger differences between means compared to the LSD, which guards against Type I error. The standard analysis of variance (ANOVA) test was performed using SPSS 17.0 statistical software to compare the treatment means for each year separately.

3. Results

3.1. *Yield attributes*

The longest main shoot of mustard was observed at 0.8 IW/CPE with or without hydrogel (Table 4). A 39.8% increase in the main shoot length was obtained with irrigation at 0.8 IW/CPE + HG over rainfed. Interestingly, the main shoot length in the rainfed crop + HG was similar to

Table 4. Yield attributes of Indian mustard as influenced by hydrogel application under variable irrigation schedules (Pooled data of 2013–14 and 2014–15).

Treatments	M S length (cm)		Branches plant^{-1}				Total siliquae plant^{-1}		1000 seed weight, gm					
	+HG	-HG	PB		SB		+HG	-HG	MS		PB		SB	
			+HG	-HG	+HG	-HG			+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	85.9^{a}	84.8^{a}	6.9^{a}	6.5^{a}	16.1^{a}	15.8^{b}	165.4^{a}	134.3^{bc}	6.82^{a}	6.53^{a}	6.37^{a}	6.21^{a}	5.98^{a}	5.81^{a}
0.6 IW/CPE	75.8^{b}	74.7^{b}	6.3^{a}	5.4b^{a}	16.4^{a}	12.9^{c}	148.5^{b}	126.0^{c}	6.23^{ab}	6.32^{b}	6.25^{a}	5.94^{b}	5.72^{a}	5.51^{b}
0. 4IW/CPE	74.1^{b}	71.1^{c}	5.5^{a}	5.5^{b}	13.1^{c}	12.5^{c}	131.8^{b}	132.4^{b}	6.26^{b}	6.18^{b}	5.79^{b}	5.41^{c}	5.36^{c}	5.06^{d}
Rainfed	70.9^{c}	65.0^{d}	4.6^{c}	3.8^{c}	11.3^{d}	9.1^{d}	122.6^{b}	106.9^{c}	6.11^{bc}	5.95^{c}	5.40^{c}	5.19^{d}	5.08^{e}	4.75^{f}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no hydrogel., PB: Primary branches, SB: Secondary branches, MS: Main Shoot. Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range test.

the crop irrigated at 0.4 IW/CPE ratio–HG, implying that supplemental irrigation in mustard can be substituted by hydrogel application without any penalty. An increase of 8.3% in the main shoot length was recorded in rainfed crop + HG over no hydrogel. A significant response of irrigation schedules and hydrogel application was recorded on the number of branches in mustard (Table 4). Branching in mustard did not improve by hydrogel application when frequent irrigations were applied at 0.8 IW/CPE. An increase of 12.2, 5.8, and 21.1%, respectively, in primary branches plant^{-1} was recorded at deficit irrigation scheduling, i.e. 0.6 and 0.4 IW/CPE ratio, and rainfed with hydrogel application, over no hydrogel. Similarly, a 19.5% increase in secondary branches occurred due to hydrogel application in rainfed treatment. The siliquae number reduced subsequently from the main shoot to secondary branches (Table 4). The highest siliquae were recorded at 0.8 IW/CPE ratio + HG. The siliquae length in the main shoot and primary branches remained at par when the crop was irrigated at 0.8 and 0.6 IW/CPE + HG (Table 4). But, under limited moisture supply and longer irrigation intervals, the siliquae length of the main shoot with irrigation at 0.4 IW/CPE + HG was superior to no hydrogel. The siliquae length (14.4 % higher) on primary branches was recorded for rainfed condition + HG over –HG. The reduction in the siliquae length at 0.4 IW/CPE-HG and rainfed condition-HG was 13.9 and 6.7%, respectively. The seeds siliqua^{-1}on the main shoot and primary branches of rainfed crop + HG increased by 17.5 and 4.1%, respectively, over–HG plots. The 1000-seed weight (TSW) was reduced from the seeds from the main shoot, primary and least from to secondary branches (Table 4). For the main shoot, a 12.8% reduction in TSW was recorded in rainfed condition–HG over 0.8 IW/CPE ratio + HG; and this reduction dropped to 10.4% when the hydrogel was added. The TSW on primary branches reduced by 4.1, 4.9, 6.3, and 7.2 % at 0.8, 0.6, 0.4, and rainfed conditions without HG, respectively. The declining trend in the correlation between seed yield and 1000-seed weight on the main shoot, primary and secondary was recorded (Figure 1 a &b). The highly positive correlation between the seed yield and 1000-seed weight of the main shoot indicates that the mustard ideotype and ideal crop geometry should be tailored in a manner where a longer main shoot length and more primary branches than secondary branches, could be achieved.

3.2. Mustard seed and oil productivity

The seed and biological yields of mustard were significantly influenced by various irrigation schedules and hydrogel application (Table 5). The increase in the seed yield with irrigation schedule at 0.8, 0.6, 0.4 IW/CPE ratios and rainfed + HG was 18.6, 19.5, 15.3, and 32.3%, respectively, over –HG. RWC, SMC at the pod filling stage had a significant impact on seed yield ($R^2 > 0.9$), however at the pre-flowering stage comparatively lesser but it is the moisture content that determines the productivity. Seed yields obtained with irrigation at 0.6 and 0.4 IW/CPE ratios + HG was similar to the two former treatments. Further, the yield from rainfed + HG plots was similar to the 0.4 IW/CPE ratio–HG. Also, the seed yield did not differ between rainfed condition + HG and 0.4 IW/CPE–HG (Table 5). The seed yield response of mustard at 0.8 IW/CPE was only 3%, which increased to 24.9% in rainfed conditions. Irrigation scheduling and use of hydrogel significantly increased the siliqua length and seeds siliqua^{-1} on the main shoot and this could be the reason for high seed yield (Figure 1 a & b). During the first year, the maximum biological yield was obtained under irrigation at 0.8 IW/CPE ratio + HG, which was similar to irrigation at 0.6 IW/CPE ratio + HG (Table 5). The biological yield obtained with irrigations at 0.8 and 0.6 IW/CPE ratio–HG and 0.4 IW/CPE ratio + HG were alike. Further, the biological yield from hydrogel applied plots was similar to the plots irrigated at 0.4 IW/CPE–HG. During the second year of the study, hydrogel did not express a significant effect at any of the irrigation schedules, i.e. 0.8, 0.6, IW/CPE, except at 0.4 IW/CPE irrigation scheduling. However, under rainfed conditions, hydrogel application improved the biological yield by 17.8%. All irrigation schedules with or without hydrogel application recovered a significantly higher oil content in seed over rainfed conditions +/– HG (Table 5). The oil yield was similar where the crop was irrigated at 0.8 IW/CPE ratio +/– HG. Likewise, the difference in oil yield due to hydrogel application under irrigations at 0.6 and 0.4 IW/CPE ratio was non-significant. Applying hydrogel in rainfed crops resulted in as much oil yield as with irrigation at 0.4IW/CPE ratio + HG during both the year.

3.3. Production indices and economics

The production efficiency (PE) of mustard irrigated at 0.8 IW/CPE ratio + HG was 14.5% higher over –HG (Table 6). The increase in PE due to hydrogel application was larger (28.3%) in the rainfed crop. The higher yield with hydrogel application leads to higher PE in mustard. The highest net returns and profitability were achieved by applying irrigation at 0.8 and 0.6 IW/CPE ratio + HG, followed by irrigation at 0.8 and 0.6 IW/CPE ratio–HG. Interestingly, the net return and profitability obtained with irrigation at 0.6 IW/CPE ratio without hydrogel were similar to those obtained under a 0.4 IW/CPE ratio with hydrogel. Moreover, by imposing hydrogel with irrigation at 0.8, 0.6, 0.4 IW/CPE and rainfed, the increasing trend in the economic gains were observed (6, 16.4, 18.1, and 28.3%, respectively) over no-hydrogel (Table 6). It further suggests that the use of hydrogel can save irrigation water besides improving yields. The net return and profitability under irrigation at 0.4 IW/CPE without hydrogel was found at par with rainfed conditions with hydrogel use. Under the rainfed condition, the application of hydrogel improved the profitability by 10.7%, over no hydrogel.

3.4. Relative water content (RWC) and soil moisture dynamics

The highest RWC was recorded with irrigation at 0.8 IW/CPE ratio with hydrogel at both pre-flowering and pod development stages (Table 7). A similar RWC with irrigations scheduled at 0.8 IW/CPE -HG and 0.6 IW/CPE + HG, indicates that the response of hydrogel is meager at higher irrigation regimes. At other irrigation regimes, hydrogel improved RWC significantly. The RWC at the pod development stage influenced seed yield significantly than at the pre-flowering stage (Figure 2). The leaf RWC under irrigation at 0.6 IW/CPE-HG hydrogel was at par with 0.4 IW/CPE + HG. Likewise, rainfed crop + HG and the crop irrigated at 0.4 IW/CPE -HG showed similar leaf RWC. The soil

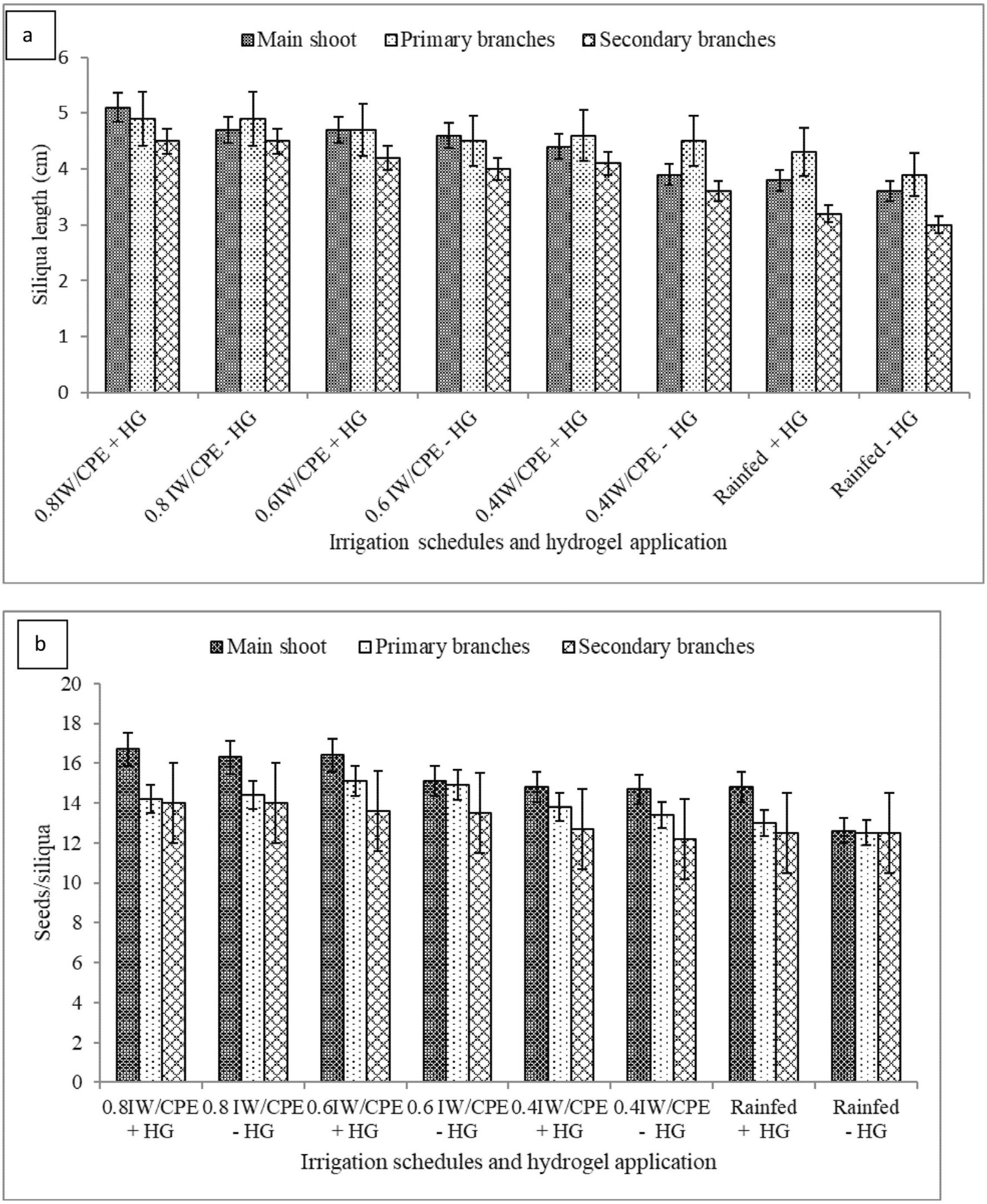

Figure 1. Effect of irrigation scheduling and use of hydrogel on siliqua length (a) and seed per siliqua (b) on main shoot primary and secondary branches.

moisture content at pre-flowering and pod filling stages remained highest infrequently irrigated at 0.8 IW/CPE with and without hydrogel application. The soil moisture content of rainfed hydrogel applied plots was similar to irrigation at 0.4 IW/CPE ratio–HG. The soil moisture content in the rest of the irrigation treatments remained at par except for the irrigation at 0.4 IW/CPE-HG. Irrigation water was applied as per the treatment and it ranged from 30–90 mm during both the years (Table 7). Higher soil moisture was maintained at all the soil depths, i.e., 0–15, 15–30, and 30–45 cm with hydrogel application over no-hydrogel at all irrigation levels (Table 8). The rainfed crop received 80 mm of effective rainfall. Irrigations at 0.6 and 0.4 IW/CPE + HG saved irrigation water use by 13.6 and 27.3% and 15.9% during 2013–14 and 2014–15, respectively over 0.8 IW/CPE + HG. The water productivity (WP) however remained similar between rainfed conditions + HG and 0.4 IW/CPE –HG, suggesting enough scope for saving irrigation water with hydrogel. The marginal and gross WP at different irrigation regimes from 0.8 to 0.6 and rainfed treatments increased with hydrogel application, over no-hydrogel also reflects the greater response of the crop to hydrogel in limited moisture conditions. During, the first year, similar WP was achieved with irrigation scheduling at 0.8 and with 0.6 IW/CPE + HG (Table 9). Also, the maximum total WP was achieved with irrigation at 0.4 IW/CPE + HG among the irrigation treatments. But, during the second year also, the response of hydrogel was not evident for 0.6 and 0.4 IW/CPE, but higher WP was recorded at 0.4 IW/CPE and rainfed.

Table 5. Year-wise seed and biological yield, harvest index; oil content and oil yield (Pooled) of Indian mustard as influenced by hydrogel application under variable irrigation schedules.

Treatments	Seed yield (kg ha^{-1})				Biological yield (kg ha^{-1})				Oil yield (kg ha^{-1})			
	2013–14		2014–15		2013–14		2014–15		2013–14		2014–15	
	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	2620^{aA}	2209^{abB}	3115^{aA}	3103^{aA}	8088^{aA}	7405^{bB}	9713^{aA}	9478^{aA}	1085^{aA}	921^{aA}	1193^{aA}	1100^{aA}
0.6 IW/CPE	2391^{bA}	1997^{cB}	2506^{bA}	2205^{bB}	8203^{aA}	6986^{bcB}	8536^{bA}	8330^{bA}	999^{abA}	837^{bB}	1016^{bA}	982^{bA}
0. 4IW/CPE	2320^{Ab}	2012^{bcB}	2413^{bA}	2123^{cB}	7503^{bA}	6452^{cB}	8265^{bA}	7582^{bcB}	972^{bA}	829^{bB}	874^{cA}	850^{cA}
Rainfed	1829^{cA}	1382^{dB}	1979^{cA}	1584^{dB}	6596^{cA}	5632^{dB}	6887^{cA}	5848^{dB}	770^{cA}	580^{cB}	773^{cA}	607^{dB}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no hydrogel. Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range test.

Table 6. Production efficiency and economics of Indian mustard as influenced by hydrogel application under variable irrigation schedules (Pooled data of 2013–14 and 2014–15).

Treatments	Net return ($\times 10^3$ INR ha^{-1})		Profitability index (Rs ha^{-1} day^{-1})		Net B:C ratio		PE (kg ha^{-1} day^{-1})	
	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	79.4^{aA}	61.2^{bB}	374^{aA}	352^{bB}	2.3^{aA}	2.0^{aB}	19.1^{aA}	17.7^{aB}
0.6 IW/CPE	79.1^{aA}	60.5^{bB}	372^{aA}	346^{bB}	2.1^{bA}	1.9^{aA}	16.3^{aA}	14.0^{bB}
0. 4IW/CPE	57.9^{bA}	45.9^{cB}	350^{bA}	315^{cB}	1.8^{cA}	1.5^{bB}	15.8^{aA}	13.8^{bB}
Rainfed	49.3^{cA}	38.6^{dB}	310^{cA}	280^{dB}	1.4^{dA}	1.1^{cB}	12.7^{bA}	9.9^{cB}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no hydrogel., PE: Production efficiency.
Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range test.

Table 7. Relative water content, soil moisture content and soil moisture tension in Indian mustard as influenced by hydrogel application under variable irrigation at pre-flowering stage (45 DAS).

	RWC %				Soil moisture content (%)				Soil moisture tension (cb)			
	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15
	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	89.2^{aA}	84.2^{aB}	90.2^{aA}	85.3^{aB}	17.3^{aA}	14.3^{aB}	16.5^{aA}	15.2^{aA}	26.3^{cA}	32.1^{cB}	26.8^{cA}	31.9^{cB}
0.6 IW/CPE	88.2^{aA}	81.1^{bB}	89.2^{aA}	82.4^{bB}	16.3^{bA}	17.7^{bA}	16.1^{bA}	16.8^{bA}	44.3^{bA}	48.1^{bB}	44.1^{bA}	49.0^{bB}
0. 4IW/CPE	82.8^{bA}	76.8^{cB}	81.5^{bA}	78.0^{bcA}	16.2^{bA}	13.2^{cB}	16.7^{bA}	14.2^{cB}	51.2^{bA}	59.2^{aB}	52.1^{bA}	60.2^{bB}
Rainfed	71.3^{cA}	65.4^{dB}	72.0^{cA}	66.0^{cB}	13.3^{cA}	13.3^{cA}	14.3^{cA}	12.8^{cB}	62.8^{aA}	79.7^{aB}	61.2^{bA}	78.9^{aB}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no hydrogel. Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range tests.

4. Discussion

The water-laden gel 'chunks' formed from HG after contact with water act as local miniature water reservoirs which helps in the initial establishment of crops resulting in better crop growth. Singh, 2012 also reported a similar release pattern of water from hydrogel under water deficit conditions for peal millet. Singh et al. (2017) spelled out that higher soil moisture retention with HG application and its subsequent gradual release for a longer period enables the plant to better utilize the root zone moisture under less frequent irrigations. The plant growth and development improves under limited irrigation and rainfed conditions in oilseed crops by higher soil moisture and optimally translocated nutrients-cum-photosynthates mediated by HG application (Sivapalan 2011; Rathore et al., 2019). The hydrogel application increases plant survival (Woodhouse and Johnson 1991) and dry matter production and prolongs the stay-green quality (Callaghan et al., 1988), particularly under moisture, constrained situations (Yangyuoru et al., 2006). The enhanced nutrient availability through enhanced longevity of water availability and uptake improves plant growth and yield attributes in hydrogel amended plots (Rathore et al., 2019, Chen et al., 2003). In the present investigation, the hydrogel application enhances the seed yield of mustard by 15.6% over no hydrogel application. However, Jat et al. (2018) reported 8.7% in grain yield improvement in mustard at the same level of soil moisture content. This variation was mainly due to soil types and climatic conditions. Under moisture-constrained situations, as the soil moisture tension increases from 10–100 kPa, the hydrogel releases nearly four times higher soil moisture (Narjary et al., 2012). A better plant canopy, higher chlorophyll content, number of branches $plant^{-1}$, siliquae $plant^{-1}$, and seeds $siliqua^{-1}$ with the addition of hydrogel has been also reported in soybean (Sivapalan 2011). The application of super absorbent polymers improves cell membrane development, leaf area index, leaf area duration, chlorophyll, and protein content by balancing nutrient substances and higher CO_2 fixation through prolonged stomata opening ascribes for the increase in yield attributes of mustard (Dexter and Miyamoto 1995; Rathore et al., 2019). Moisture deficiency at the critical stages reduces the plant crown diameter and at the siliquae development stage, even if siliquae formation is there, the siliquae length significantly reduces. The large quantities of water and nutrients retained near the rhizosphere zone with hydrogel applications are released in synchrony with plant demand (Bhardwaj et al., 2007). The hydrogel enables water and nutrient extraction from wider and deeper soil depths by plants, and thereby, increases nitrogen, phosphorus, potassium, calcium, and magnesium uptake resulting in better growth and yield attributes (Mandal et al., 2015). The increasing order of the reduction in TSW from sufficient to deficit irrigation and rainfed condition with hydrogel application is indicative of a larger advantage of hydrogel use under

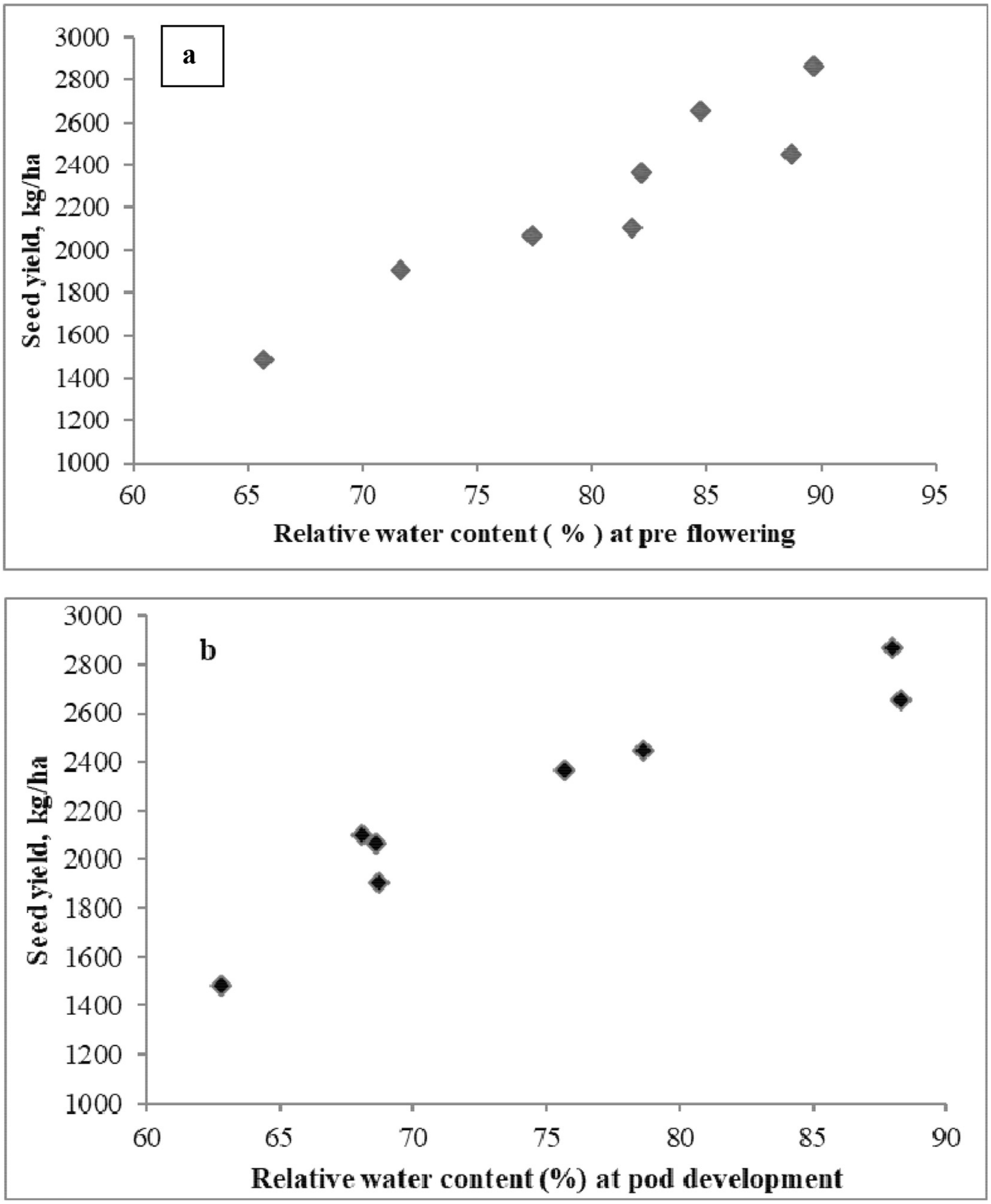

Figure 2. Relationship of mustard seed yield and relative water content (RWC) at prefolowering and pod development stage.

Table 8. Relative water content, soil moisture content and soil moisture tension in Indian mustard as influenced by hydrogel application under variable irrigation at peak pod development stage (80 DAS).

	RWC %				Soil moisture content (%)				Soil moisture tension (cb)			
	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15
	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	88.1^{aA}	88.4^{aA}	87.8^{aA}	88.2^{aA}	16.2^{aA}	15.2aA	16.5^{aA}	15.4^{aA}	39.9^{cA}	38.9^{cA}	38.5^{bA}	37.9^{bA}
0.6 IW/CPE	78.1^{bA}	68.2^{cB}	79.2^{bA}	68.0^{cB}	14.2^{bA}	12.8^{bB}	13.9^{bA}	12.1^{bA}	48.8^{bA}	45.2^{bB}	47.8^{bA}	46.0^{bA}
0. 4IW/CPE	75.3^{bA}	68.2^{cB}	76.1^{b}	69.0^{cB}	12.8^{bA}	11.1^{cA}	12.0^{bA}	11.4^{bcA}	73.9^{aA}	73.9^{aA}	67.5^{aA}	74.0^{aA}
Rainfed	69.2^{cA}	63.3^{dB}	68.2^{cA}	62.3^{dB}	10.6^{cA}	9.4^{cB}	10.8^{bcA}	10.1^{cA}	75.2^{aA}	78.2B	71.0^{aA}	78.0^{aB}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no hydrogel. Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range tests.

Table 9. Water productivity of Indian mustard as influenced by hydrogel application under variable irrigation schedules.

Irrigation scheduling/Hydrogel	WP (kg seed/ha-mm)				Marginal WP (kg seed/ha-mm applied)				Gross WP (kg seed/ha-mm total irrigation used)			
	2013–14		2014–15		2013–14		2014–15		2013–14		2014–15	
	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG	+HG	-HG
0.8IW/CPE	16.4^{aA}	13.8^{bA}	20.3^{aA}	20.2^{aA}	29.1^{bA}	24.5^{cB}	34.6^{cA}	34.5^{bA}	29.1^{bA}	24.5^{bB}	34.6^{bA}	34.5^{bA}
0.6 IW/CPE	14.9^{abA}	12.5^{bB}	16.3^{bA}	14.4^{bcB}	39.9^{bA}	33.3^{bB}	41.8^{bA}	36.8^{bB}	39.9^{bA}	33.3^{bA}	41.8^{bA}	36.8^{bB}
0. 4IW/CPE	14.5^{abA}	12.6^{bB}	15.7^{bA}	13.8^{cB}	77.3^{aA}	67.1^{aB}	80.4^{aA}	70.8^{aB}	77.3^{aA}	67.1^{aB}	80.4^{aA}	70.8^{aB}
Rainfed	11.4^{bcA}	8.6^{cB}	12.9^{cA}	10.3^{dB}	-	-	-	-	14.1^{cA}	10.6^{cB}	20.1^{cA}	16.0^{cB}

IW: Irrigation water, CPE: Cumulative pan evaporation, +HG: with Hydrogel, -HG: no Hydrogel., WP: Water productivity. Same letter within each column indicates no significant difference among the treatments (at $P < 0.05$) according to Duncan's multiple range tests.

moisture-stressed environments. The spot placement of hydrogel under moisture-stressed conditions gives an initial boost to plants in-terms of early emergence and seedling establishment, but under a higher number of secondary branches, the TSW drops. Enhanced root development and plant growth regulation by improvement in water-retention capacity and cluster structures of soil through hydrogel are useful in achieving higher production (Akelah, 2013). Similar results of yield advantage and higher nutrient uptake have been reported by (Singh et al., 2017) in mustard, (Rathore et al., 2019), in pearl millet, and by (Dai et al., 2017) in sorghum.

Pusa hydrogel is capable of holding water 300–500 times its weight and the gradual release of moisture helps in retaining soil moisture towards the maturity stage of the crop which prolongs the seed filling and oil bio-synthesis period (Shim et al., 2003). Not only oil content, but the quality of the oil is also positively influenced by the hydrogel. Hydrogel application increases sink capacity in the plant which provides enough time to prepare unsaturated fatty acids from the saturated fatty acids in mustard (Tohidi-Moghadam et al., 2011). The moisture absorbed by polymer from the surrounding soils is maintained near the seed surface, which execrates germination and enhances the total number of germinated seeds (Akelah 2013). The modified cation exchange capacity of the soil and enhanced nutritional and water status of plants through hydrogel as a soil conditioner and ameliorant further improve soil aeration and soil-microbial activities. It delays fertilizer dissolution and increases sorption capacity and nutrient uptake by plants and finally the yield (Jhurry et al., 2001). A favorable soil-water-plant continuum aided by hydrogel has indirect nutritional benefits also, besides providing higher moisture availability for producing better yields (Seybold 1994). The economics thus improves due to higher fertilizer recovery also (Li and Zhang 2010). An increase in the water holding capacity of soil due to hydrogel significantly reduces the irrigation requirement of many plants, and thus, the cost involved in irrigation can be saved. The over-all B: C ratio indicates that the higher economics could be obtained with hydrogel application at low irrigation regimes. The moisture stays captured in a hydrogel embedded soil due to declined deep percolation, reduced evaporation, seepage, surface runoff losses in sandy soils. In a compatible aqueous soil, they make a three-dimensional swollen network, they store water as well as plant nutrients dissolved in the water, and gradually releases both moisture and nutrients as needed (Sharma 2004). Through polymer swelling, hydrophilic polymers can build an additional water reservoir for the plant-soil system and thereby reduce water stress in plants. The wilting in plants in hydrogel amended soil is slower over no-hydrogel (Narjary et al., 2012) due to decreased hydraulic conductivity and reduced drainage of water below the root zone (El-Hady and Camilia, 2006). Hydrogel accumulates the gravitation water in the soil through deeper and denser rooting (Rathore et al., 2019), which under natural conditions rapidly permeates the soil profile and becomes unavailable to plants. As a soil conditioner it improves water-transmitting properties *viz.* infiltration rate, hydraulic conductivity, moisture content at field capacity and wilting point, and thus the available water for plants (Akhter et al., 2004; Hayat and Ali 2004). It suggests that hydrogel maintains a favorable soil moisture balance even when the irrigation intervals are longer (Allahdadi et al., 2005). In the water availability range of plants (10–100 kPa), the soil water release per unit of suction changes for sandy soils has been reported to be almost 4-time higher in hydrogel applied soils over no-hydrogel. Thus, the use of hydrogel inflates the inter-irrigation period and the time of arrival of critical soil moisture constant is delayed (Narjary et al., 2012) thus reduces the amount of irrigation water, frequency of irrigation, and total crop water requirement from 55 to 80% (Singh et al., 2017). The improvement in soil physical properties, including mean weight diameter of soil aggregates, water-stable structural units, relative field capacity, retention pores, and structural coefficient. At the same time, it reduces transmission pores, penetration resistance, and saturated hydraulic conductivity (Narjary and Aggarwal, 2014) and maintains low soil moisture tension, particularly in the sand soils (Kalhapure et al., 2015; Baasiri et al., 1986).

Hydrogel holds great promise in reducing soil moisture tension by improving soil moisture under moisture-stressed conditions (Wang et al., 2003). The light textured soils under semi-arid and arid areas are moisture and nutrient-poor (Riofrio and Wittmeyer 1992; Li et al., 2004) where, large pores facilitate quick moisture losses, fast organic carbon decomposition and poor water retention drain away from the nutrients also, often before plants can absorb them for their use. Water and nutrient adsorption through adhesion between inter-and intra-aggregate soil particles and gel (Akhter et al., 2004) activate favorable chemical reactions in the soil (El-Hady and Camilia 2006). Hydrogel provides a reservoir of soil water in the root zone by preventing leaching and deep percolation losses (Sow et al., 1997). The higher retention pores and low saturated hydraulic conductivity under hydrogel amended soil reduces the drainage pores (Paluszek and Zembrowski 2008), thereby, maintain a higher moisture level (Al-Darby 1996; Al-Omran and Al-Harbi 1998). This typical feature of intense water storage and release of hydrogels enables the sandy soil to retain more water (Sivapalan, 2011) and provides a shield against temporary drought stress and reduces the risk of total crop failure (DE Boot 1990; Langaroodi et al., 2013). The highest energy productivity under irrigation at 0.6 IW/CPE without hydrogel application was recorded due to higher bio-energy accumulation and low energy input in the treatment. Energy efficiency improvement and sustainable energy management through the use of hydrogels can potentially increase yield and save energy inputs without compromising yields (Singh et al., 2004). Super absorbent polymers decrease the frequency of irrigation by increasing irrigation interval, therefore water cost and energy will be saved (Sivapalan 2011). The positive energy balance is the outcome of increasing the water storage capacity of soil consequent to hydrogel application (Rathore et al., 2014a,b; Montesano et al., 2015).

5. Conclusion

The two-year study suggests that the use of hydrogel improves mustard production levels, economics, water- and energy- balance under both deficit irrigation and rainfed situations. The limited irrigation water with the use of hydrogel could be adequately utilized to mitigate moisture stress in the crop under deficit irrigation of 0.4 IW/CPE ratios and to some extent under rainfed conditions. Nevertheless, before advocating hydrogel, water retention and transmission characteristics under different textures and type of soils should be thoroughly studied. Finding out the compatibility with other conditioners and bringing down the cost of the gel also remain challenges before the researchers.

Declarations

Author contribution statement

Sanjay Singh Rathore: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kapila Shekhawat: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Subhash Babu, VK Singh: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

The authors are unable or have chosen not to specify which data has been used.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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